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HYBRID-PULSE CODING: an experimental quadrature modulation system for television transmission

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HYBRID-PULSE CODING: AN EXPERIMENTAL QUADRATURE MODULATION SYSTEM FOR TELEVISION TRANSMISSION

R.V. Harvey, B.Sc., M.I.E.E.

Summary

A comparison of p.c.m. and hybrid p.c.m. is given and experimental tests on a particular h.p.c.m. system are described. The limitations and difficulties of a system using h.p.c.m., both fundamental and instrumental, are discussed. It is concluded that, while the efficiency offered by a h.p.c.m. transmission system can approach the theoretical limit, this demands a high order of instrumentation and the performance is sensitive to propagation effects such as multiple paths.

Issued under the authority of

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(EL-75)

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HYBRID-PULSE CODING: AN EXPERIMENTAL QUADRATURE MODULATION SYSTEM FOR TELEVISION TRANSMISSION

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1. Introduction

The design of a multi-level p.c.m. transmission system is usually determined by two factors. First, the performance must be satisfactory in the absence of transmission noise and second, the threshold carrier-to-noise ratio at which errors become significant must be below the carrier-to-noise ratio which is exceeded for a large proportion of the time. If the error rate is too high at the available carrier-to-noise ratio, the threshold must be reduced by re-coding the transmitted digits to have fewer levels and so the digit rate must be increased to preserve the bit rate. If, above the threshold, the quantising noise is too high, the number of quanta must be increased, requiring either more levels in each digit or a higher digit rate. Thus an improvement in either respect requires a greater bandwidth.

A hybrid p.c.m. (h.p.c.m.) system may be regarded as derived from a particular p.c.m. system, whereby the least significant digit of each word is replaced by an analogue pulse which represents the remainder of the original signal after the digital signal value has been subtracted from it. The h.p.c.m. signal will have the same threshold level as the p.c.m. signal, as this is determined by errors in the most significant digit, but there will be no noise introduced by the quantising process. Above the threshold, the h.p.c.m. will have the characteristics of an analogue signal but with an improvement in signal-to-noise voltage ratio which is numerically equal to the number of steps in the quantised part of the signal.

Thus, the h.p.c.m. signal gives a higher signal-to-noise ratio than a p.c.m. system with the same signalling rate, bandwidth and threshold. Alternatively, by reducing the number of digital pulses, the h.p.c.m. system offers a reduction in bandwidth at the cost of lower performance at carrier-to-noise ratios between the threshold and some arbitrary higher value. If this saving were carried to the limit, the system design would degenerate progressively into that of a pure analogue system. This flexibility is particularly attractive when the carrier-to-noise ratio is varying as, for example, in fading conditions; in such circumstances two performance standards are sometimes specified for two signal levels, allowing a lower performance at the lower level in order to make a realistic allowance for the statistics of a fading signal. In previous investigations,[1,2,3] emphasis was placed on the performance of a h.p.c.m. system operating in a baseband channel and Reference 4 gives a theoretical comparison of h.p.c.m. with other digital and analogue systems. The present report is concerned mainly with the problems of transmission by a modulated carrier.

2. A comparison of systems for television signals

Fig. 1 illustrates the performance of some p.c.m. and h.p.c.m. systems suitable for television, assuming that the coded baseband signal is carried by a double-sideband amplitude-modulated suppressed-carrier (d.s.b. a.m. s.c.) r.f. signal which is synchronously demodulated. Some of the relevant features of Fig. 1 are given in Table 1. Since the r.f. carrier is suppressed in the modulator, the term carrier-to-noise ratio is replaced by the signal-to-noise ratio at the demodulator input (i.s.n.r.) which is defined as the ratio of the maximum r.m.s. value of the modulated r.f. signal to the r.m.s. noise. The output signal-to-noise ratio (o.s.n.r.) is defined as the ratio of the peak-to-peak demodulated signal to the r.m.s. noise after demodulation.

The r.f. bandwidth required by each system is always twice the coded baseband bandwidth and is proportional to the number of pulses per word, n, taking the analogue system as a reference, as shown in Table 1. Table 1 also gives comparative figures for an analogue signal, with and without carrier suppression; if the carrier is suppressed, the ratio o.s.n.r./i.s.n.r. will be 9 dB, as shown by the diagonal line in Fig. 1.

The graphs of Fig. 1 are labelled with the total number of pulses in each p.c.m. or h.p.c.m. word, n, and the number of levels in each of the quantised pulses or digits, M. As will be seen, the graphs for p.c.m. each have a maximum value which is determined by the quantising noise. An expression for the output signal-to-r.m.s.-quantising-noise ratio is given in Reference 4 and may be taken to be $11 + 6x$, expressed in dB, where x is the number of bits in the p.c.m. word, $n \log_2 M$.

For high-quality television pictures, a p.c.m. system using linear quantising requires an 8-bit word to describe each picture element in sufficient detail so as to reduce the quantising noise to an acceptable level, including an allowance for up to four tandem coding and decoding processes. The p.c.m. coder may produce, for each word, either 8 binary digits, 4 four-level digits, 2 sixteen-level digits, or one 256-level digit, according to the available bandwidth and the required i.s.n.r. threshold. Above this threshold, however, there will be no digit errors but the signal-to-quantising noise ratio will be, in each case, 59 dB (peak-to-peak composite signal, unweighted).

It should be noted that the threshold i.s.n.r. is defined as being that at which the peaks of the noise cause a digit error rate of 10^{-6}. The onset of impairments caused by

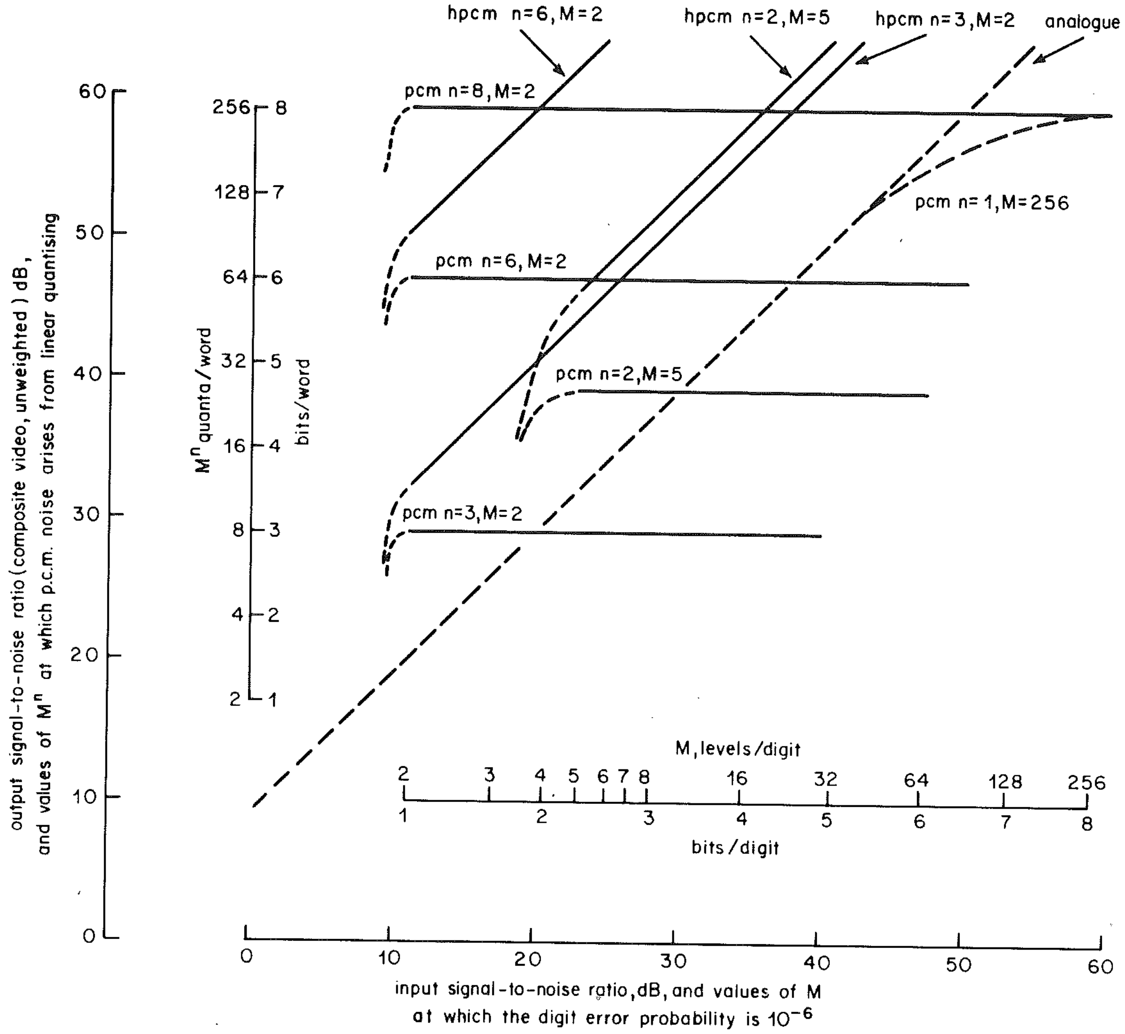

Fig. 1 - Signal-to-noise ratios for p.c.m. and h.p.c.m. systems with n pulses per word and M levels per digit

digit errors is rapid for a binary signal with no system of error detection or concealment, when the i.s.n.r. falls below the threshold value. However, as the number of levels in the most significant digit, M, is increased, the onset of impairments becomes less well defined and the threshold becomes 'softer'. In the limit the p.c.m. television word could be a single 256-level digit, when the threshold would be very soft and would approximate to the analogue s.n.r. curve.

6-bit binary p.c.m. will give a o.s.n.r. of 47 dB (peak-to-peak composite signal, unweighted) which is not adequate for linear coding but gives a 25% bandwidth reduction in comparison with 8-bit p.c.m. for the same threshold. But h.p.c.m. with 5 binary digits and one analogue pulse (n = 6, M = 2) will have the same threshold i.s.n.r. of 11 dB and will have an o.s.n.r. reaching 59 dB at 20 dB i.s.n.r., thus again saving 25% bandwidth at the cost of a lower o.s.n.r. between the two input levels. A mathematical treatment of these conditions is given in an Appendix.

3. An experimental h.p.c.m. television system using quadrature modulation

3.1. A two-pulse h.p.c.m. system

The third example of h.p.c.m. given in Table 1 is a two-pulse five-level system with a threshold i.s.n.r. of 23 dB. A system of this type was investigated experimentally in the laboratory. Compared with a suppressed-carrier analogue system, this h.p.c.m. system gives an improvement of 14 dB in o.s.n.r. at input levels above the threshold, but it requires twice the r.f. bandwidth, assuming d.s.b. modulation in all cases. The need for twice the r.f. bandwidth arises because two pulses are to be sent for each word, requiring either twice the transmission rate or two channels. However, the two channels can be combined by quadrature modulation if the two signal pulses, one 5-level digit and one analogue difference pulse, are d.s.b. modulated on to two carriers of the same frequency, but in phase-quadrature with each other. The total signal power is unchanged but the quadrature modulated signal requires one-half the r.f. bandwidth, now being equal to that of the d.s.b. analogue signal. As a result of the reduced bandwidth, the i.s.n.r. at threshold is increased by 3 dB; these requirements are given under h.p.c.m./q.m. in Table 1.

The basic operation of quantising and quadrature modulation is illustrated in Fig. 2 and the signal processing is shown in the schematic of Fig. 3.

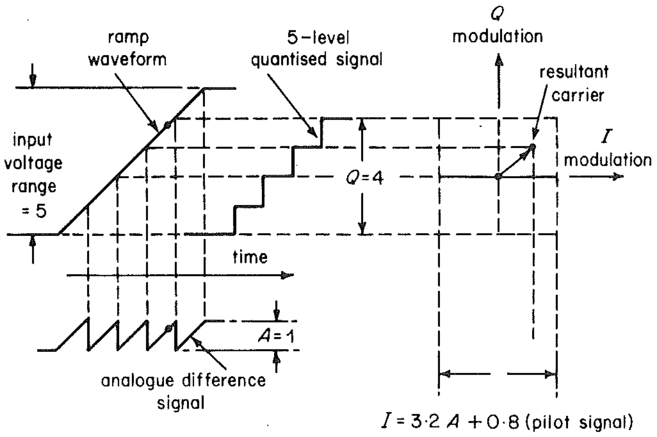

Fig. 2 - Two-pulse h.p.c.m. with five-level quantising using quadrature modulation with pilot signal

3.2. The quadrature modulator

A quadrature modulator and demodulator had already been developed[5] for analogue television and its performance was satisfactory for the present purpose. The functions of modulator and demodulator are included in Fig. 3. The quadrature signals were demodulated synchronously and the identity of the two signals was maintained by locking the phase of the local oscillator so that a 6 MHz pilot carrier, added to the I signal, was present only at the corresponding output.

3.3. Description of operation

Referring to the schematic of Fig. 3 the television signal is first sampled, held and quantised into five levels and the quantised signal is then subtracted from the original analogue signal. After filtering, the quantised and analogue

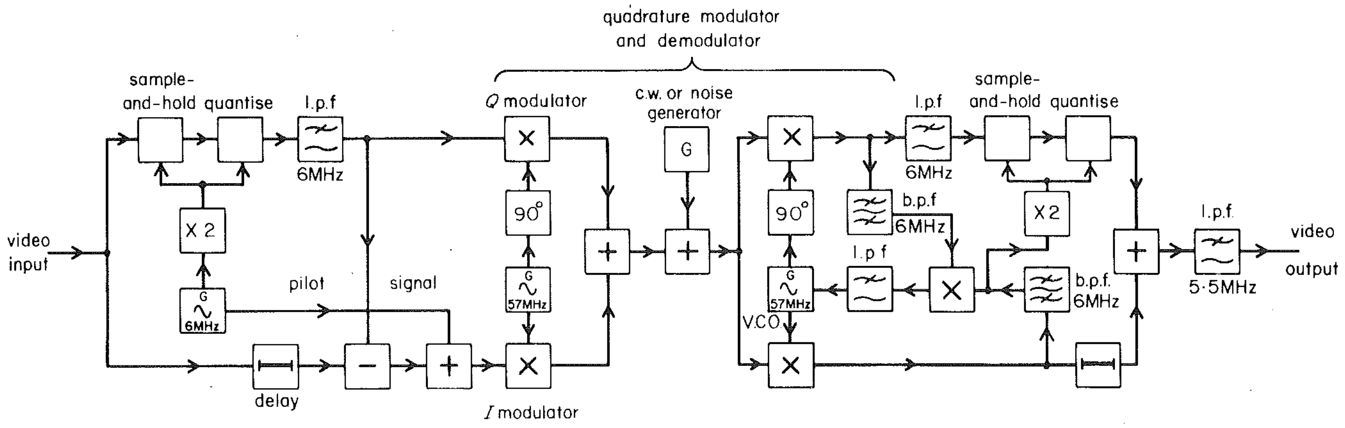

Fig. 3 - Schematic of experimental h.p.c.m. system for television

TABLE 1

System	Pulses per word, n	Levels per pulse, M	o.s.n.r. at threshold dB	i.s.n.r. at threshold dB	i.s.n.r. at o.s.n.r. = 59 dB	bandwidth for d.s.b. a.m. s.c. ref. analogue system
p.c.m.	8	2	59	11	11	8
	6	2	47	11	–	6
	3	2	29	11	–	3
	2	5	39	23	–	2
	2	16	59	34·5	34·5	2
h.p.c.m.	6	2	50	11	20	6
	3	2	32	11	38	3
	2	5	46	23	36	2
h.p.c.m./q.m.	2	5	46	26	39	1
Analogue s.c.	1	–	(20 at	11)	50	1
Analogue full-carrier	1	–	(14 at	11)	56	1

Note: For television standard I the o.s.n.r. given above must be reduced by 5 dB to give the peak-to-peak luminance/r.m.s. noise ratio (unweighted).

difference signals are applied to the two modulators driven in quadrature by the same 57 MHz carrier source. The 12 MHz sampling signal is derived from a 6 MHz source which also supplies the pilot signal which is added to the analogue signal at the input to its modulator. The outputs of the modulators are added and noise or c.w. interference may also be added, before the signal reaches the demodulator, for test purposes. The quadrature demodulator is driven by a voltage-controlled oscillator which is steered by a phase-locked loop to the correct frequency and phase, indicated by a null in the output of a 6 MHz detector in the quantised signal path. The 6 MHz signal then present in the analogue signal path is doubled in frequency and delayed to provide the drive for the re-sampling process.

In the experimental equipment, the phase-locked condition was satisfied by two carrier phases 180° apart, one of which reverses the polarity of the signal in each channel. There was no attempt to remove the ambiguity of sign in the demodulated signal since it could be made correct simply by removing the signal a few times until the carrier locked in the correct sense. An operational system could easily overcome this defect by more elegant means. After re-sampling and re-quantising the digital signal, it was added to the analogue difference signal and filtered to produce the reconstituted signal output.

3.4. Filtering and timing

After the initial sampling and quantising process, the signal was restricted in bandwidth by a single low-pass filter which had a 3 dB attenuation at 6 MHz, half the sampling frequency. The delay in this process must be accompanied by a compensating delay in the analogue signal before subtraction and modulation. Any delay in the subtractor should also, ideally, be compensated before modulation. The accuracy of delay compensation can be checked to ensure that when the two signals from the demodulator are added in a suitable resistive network the resultant is free of transients at times when the quantum level changes.

The modulators imposed no significant bandwidth restriction on the signals and the r.f. channel bandwidth was not intentionally restricted. However, to simulate r.f. band-limiting, a second low-pass filter, similar to the first post-quantising filter was added before the re-sampling and re-quantising process, so that the overall spectrum of the digital signal was about 6 dB down at 6 MHz. Again, compensating cable delay was added in the analogue signal path before recombining the two signal at the output.

Amplifiers at the sending terminal (with corresponding attenuation at the receiving terminal) were required in the analogue signal path to raise the level of the difference signal so as to give the same maximum carrier amplitude as the digital signal, allowing 2 dB for the 20%, 6 MHz pilot and timing signal.

3.5. Performance of the experimental system

The quadrature modulator and demodulator and the phase-locked loop behaved well, apart from the unresolved ambiguity in the sign of the modulation. The signals emerging from the demodulators could be recombined to provide a transient-free picture. Difficulties arose, however, in the re-sampling process causing inter-digit interference near transitions in the digital signal. These could be minimised by careful timing of the clocking signal from the 6 MHz doubler. Some reduction in errors could also be obtained by altering the sampling frequency to allow for errors in the response of the filters at 6 MHz. But some errors remained in the absence of noise, giving a 'sparkle' of light and dark spots in the region of a step in the digital signals. A possible reason for this phenomenon is given in Section 4. Frequent adjustment of the r.f. level was required so as to ensure that the levels transmitted by the digital signal exactly coincided with those of the level comparator in the re-quantiser.

These defects made it impossible to conduct valid subjective tests on the system. Nevertheless, it was clear from the effects of injecting r.f. interference and noise that the system was behaving as expected above and below the threshold i.s.n.r. For example, when the analogue and quantised signals were made equal in maximum value and the combined, maximum r.f. signal was 4 mV r.m.s., a c.w. signal of 0·7 mV r.m.s. (i.e. a signal-to-interference ratio of 15 dB) was just below the threshold level, producing a beat pattern, via the analogue signal, with a peak-to-peak (composite signal)-to-r.m.s. interference ratio of 33 dB. An increase in the interfering signal level of 1 dB produced a coarse beat pattern of lighter and darker patches on the picture. It was noticed that, below the threshold i.s.n.r., digital errors caused by noise were considerably less annoying than those of a binary system. This is because the most significant errors are only one-fifth of the total signal amplitude in this particular h.p.c.m. system. The observed results are discussed in Section 5.

4. Operational requirements for a practical system

The difficulties encountered in the experimental system undoubtedly stem from inter-digit errors caused by imperfections in filtering and re-sampling. A practical system would therefore require a greater usage of bandwidth in order to accommodate a more gentle and controllable roll-off in filter response. A roll-off of about 50%, requiring a 50% increase over the minimum bandwidth, is probably a good compromise and would enable accurate re-sampling to be achieved with a reasonable degree of equalisation.

Sideband asymmetry was not investigated in the experimental system but it was clear that this can lead to crosstalk between the two channels and also to inter-digit interference in the digital channel. The effects of sideband asymmetry in a quadrature-modulated system have been calculated,[5] and show that an amplitude response/frequency characteristic with a skew-symmetry of ± a% leads to a crosstalk of a% which is in phase quadrature with the signal.

In a d.s.b. television system, for example, a single reflected signal with a relative amplitude of 20% and a path difference of 10 metres could, for a particular phase, cause a sinusoidal skew-symmetry of ± 20% peak giving an average skew-symmetry of about ±12%. Such asymmetry can lead to objectionable crosstalk in the h.p.c.m. system which was examined, in the following way.

A small change in the video signal level, which would occur in a picture of a cloudy sky, for example, will frequently cause the quantised signal to change from one level to the next, giving a step of 25% of the peak-to-peak quantised signal amplitude. In such conditions, the analogue difference signal will execute a step in the opposite sense which is nearly complementary but is amplified to the full peak-to-peak amplitude (ignoring the pilot signal) as shown in Fig. 2. A skew-symmetry of ±12% will therefore cause the analogue signal step to induce, by crosstalk, a 12% amplitude impulse in the quantised signal as it executes its 25% transition in level. This impulse will tend to cause errors in re-sampling and may result in quantum errors, even in the absence of transmission noise. These errors will depend on the amplitude and phase of the asymmetry and on the relative timing of the two h.p.c.m. signals and they will be most objectionable if they occur in low-contrast areas of the picture. Asymmetry will increase as the bandwidth increases but the digit errors are likely to be more controllable with a greater bandwidth.

The most stringent requirement of a practical system is that of linearity and level control, in order that the re-quantising is performed at the correct levels. In the presence of fading propagation conditions, a 25% loss of signal would cause errors in the outer digital levels; these would appear as a 20% crushing of both black and white levels in the picture. An automatic gain control system is therefore essential; this could be provided by sensing the level of the 6 MHz sidebands. But, if the fading is a function of frequency, this could lead to errors, as shown above, unless a form of adaptive equaliser were employed.

5. Discussion

The theory given in the Appendix and the values given in Table 1, show that a 2-pulse, 5-level h.p.c.m. system using d.s.b. a.m. with a suppressed carrier has a threshold i.s.n.r. of 23 dB, and a (composite) o.s.n.r. of 46 dB at threshold. This gives a basic s.n.r. improvement of 20 dB compared with an analogue system with full carrier but requires twice the bandwidth. The extra bandwidth can, ideally, be saved by using a quadrature modulator and demodulator; the threshold i.s.n.r. then rises by 3 dB to 26 dB and the addition of a pilot signal reduces the o.s.n.r. by, say, 2 dB to 44 dB, giving a reduced net improvement of 15 dB over a full-carrier analogue system.

The measurements which were carried out on an experimental h.p.c.m. system, described in Section 3.5, showed that, for c.w. interference the threshold i.s.n.r. was 15 dB and the o.n.s.r. was 33 dB. We may deduce the corresponding ratios for noise giving an error probability of 10^{-6} by adding 11 dB, giving 26 dB and 44 dB, respectively, and confirming the values derived theoretically.

In order to avoid inter-digit errors in a practical h.p.c.m. system, the bandwidth must be increased by about 50% over the ideal theoretical value. The 2-pulse, 5-level h.p.c.m. quadrature modulated system would then show an o.s.n.r. advantage of about 13 dB over a full carrier d.s.b. analogue system with the same maximum power, but with the disadvantages of requiring 50% greater bandwidth and exhibiting higher susceptibility to propagation defects, as described in Section 4.

6. Conclusions

The tests carried out on an experimental h.p.c.m. system confirm the theoretical predictions for the threshold input and output signal-to-noise ratios, but indicate certain defects which need to be overcome before a practical system can be successful. In addition, certain restraints imposed by the h.p.c.m. system pose problems which may be stringent in practical conditions, particularly in conditions of fading. The use of quadrature modulation enables the bandwidth requirement of a two-pulse h.p.c.m. system to be confined to about 50% more than that of an analogue d.s.b. a.m. system. Although capable of giving a satisfactory video signal-to-noise ratio for a lower r.f. signal power than in an analogue system, h.p.c.m. is subject to digit errors caused by crosstalk if multipath propagation conditions exist.

It seems therefore that a h.p.c.m. system using quadrature modulation would be attractive for operation only over channels having a constant gain and an accurately-controlled frequency response, and in a situation where the need for maximum saving of signal power and/or bandwidth would justify the careful instrumentation required.

7. References

1. Hybrid-pulse coding: theoretical assessment of system. BBC Research Department Report No. 1969/40.
2. Hybrid-pulse coding: experimental assessment of system as applied to video signals. BBC Research Department Report No. 1969/45.
3. Hybrid-pulse coding: experimental equipment for tests with video signals. BBC Research Department Report No. 1969/46.
4. Modulation systems for television: theoretical comparison of noise performance, with and without pulse coding. BBC Research Department Report No. 1970/39.
5. An experimental quadrature modulation system for video signals. BBC Research Department Report No. 1971/30.

8. Appendix

Signal and carrier-to-noise ratios in p.c.m. and h.p.c.m. systems

Consider a d.s.b. a.m. system with suppressed-carrier modulation and a r.f. bandwidth limited to twice the baseband bandwidth. The peak-to-peak(composite) output signal-to-r.m.s. noise ratio, o.s.n.r. in terms of the r.m.s. r.f. input signal-to-noise ratio, i.s.n.r. is given by

$$\frac{\text{o.s.n.r.}}{\text{i.s.n.r.}} = 2\sqrt{2}$$

for analogue signals; hence the broken, diagonal line in Fig. 1 with an intercept at 9 dB o.s.n.r.

The threshold i.s.n.r. for an error rate of 10^{-6} in a p.c.m. signal having M levels per digit (M—1 steps) is taken as that for which the r.m.s. noise level is 20 dB below the step height and is therefore

$$\text{i.s.n.r. (threshold)} = \frac{10}{2\sqrt{2}}(M-1)$$

for p.c.m. signals; hence the scale above the abscissa of Fig. 1 starting at 11 dB i.s.n.r. for M = 2.

The signal-to-quantising noise ratio for p.c.m. signals with n, M-level digits per word is determined by the number of quanta M^n into which the original signal range is divided, and so

$$\text{o.s.n.r. (quantising)} = 2\sqrt{3}\,M^n$$

for p.c.m. signals; hence the scale to the right of ordinate in Fig. 1 giving

$$\text{o.s.n.r. (dB)} = 11 + 20n \log_{10} M$$

For a h.p.c.m. signal with n—1 M-level digits and one analogue-difference pulse, the o.s.n.r. will be M^{n-1} times the o.s.n.r. of an analogue-signal, and therefore

$$\frac{\text{o.s.n.r.}}{\text{i.s.n.r.}} = 2\sqrt{2}\,M^{n-1}$$

for h.p.c.m. signals above the threshold; hence the full diagonal lines in Fig. 1 representing

$$\text{o.s.n.r. (dB)} = \text{i.s.n.r. (dB)} + 9 + 20\,(n-1) \log_{10} M$$

The improvement in o.s.n.r. of n-digit h.p.c.m., over n-digit p.c.m. can be shown from the above to be, at the threshold,

$$\frac{\text{o.s.n.r. (h.p.c.m.)}}{\text{o.s.n.r. (p.c.m.)}} = \frac{5}{\sqrt{3}}\,\frac{M-1}{M}$$

which approaches 9 dB for large values of M. However, it should be realised that the threshold at which the p.c.m. error rate is 10^{-6} is most significant for a binary p.c.m. system and is less significant when M is large. This 'softening' of the threshold means that the h.p.c.m./p.c.m. improvement is less than 9 dB at the effective p.c.m. threshold.

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